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Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia

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[1] Ensemble simulations of a regional climate model (RegCM3) forced by aerosol radiative forcing suggest that biomass burning aerosols can work against the seasonal monsoon circulation transition, thus re-enforce the dry season rainfall pattern for Southern Amazonia. Strongly absorbing smoke aerosols warm and stabilize the lower troposphere within the smoke center in southern Amazonia (where aerosol optical depth >0.3). These changes increase the surface pressure in the smoke center, weaken the southward surface pressure gradient between northern and southern Amazonia, and consequently induce an anomalous moisture divergence in the smoke center and an anomalous convergence in northwestern Amazonia (5°S-5°N, 60°W-70°W). The increased atmospheric thermodynamic stability, surface pressure, and divergent flow in Southern Amazonia may inhibit synoptic cyclonic activities propagated from extratropical South America, and re-enforce winter-like synoptic cyclonic activities and rainfall in southeastern Brazil, Paraguay and northeastern Argentina. **Citation:** Zhang, Y., R. Fu, H. Yu, Y. Qian, R. Dickinson, M. A. F. Silva Dias, P. L. da Silva Dias, and K. Fernandes (2009), Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia, *Geophys. Res. Lett.*, *36*, L10814, doi:10.1029/2009GL037180.

1. Introduction

[2] Smoke aerosols from biomass burning dominate the atmospheric aerosol composition of the Amazonia from June to October [*Andreae et al.*, 1988]. These smoke aerosols are mostly black and organic carbon. The former strongly absorbs solar radiation whereas the latter primarily scatters solar radiation [*Penner et al.*, 1992; *Hobbs et al.*, 1997]. These smoke aerosols reduce the surface solar flux, heat the local atmosphere, and thus modify atmospheric thermodynamic structure [*Yu et al.*, 2002]. These changes perturb regional circulation, cloud and the land-atmosphere interactions [*Koren et al.*, 2004; *Zhang et al.*, 2008].

[3] Many previous papers have investigated how smoke aerosols influence clouds, convection and the monsoon circulation of South America through field experiment, satellite observation and model simulations [e.g., *Andreae et al.*, 2004; *Kaufman and Koren*, 2006; *Yu et al.*, 2007; *Liu*, 2005]. In particular, *Liu* [2005] and *Liu et al.* [2005] suggested that aerosol from biomass burning can weaken the South American monsoon circulation as inferred from a regional climate model with spatially uniform aerosol radiative forcing. However, it is not clear whether more realistic aerosol radiative forcing would cause significant circulation response, and if so, how such a response would influence the mechanisms that control the monsoon onset. *Zhang et al.* [2008] used spatially varying aerosol forcing and a regional climate model with improved land surface energy partitioning to examine the impact of smoke aerosols on the diurnal cycle of the atmospheric boundary layer and cloudiness over Amazonia. E. Vendrasco et al. (A case study of the radiative effect of biomass burning in the precipitation: The Cuiabá-Santarém (eastern Amazon) case, submitted to *Meteorology and Atmospheric Physics*, 2008) explored two mechanisms: (a) the thermodynamic forcing tends to stabilize the lower atmosphere and (b) the dynamic response may weaken the thermodynamic forcing. The present study differs from previous work by focusing on how the circulation change induced by aerosols would interfere with the mechanisms that control the monsoon circulation transition. In doing so, it contributes to an understanding of the local and remote impacts of aerosols on rainfall patterns. As in the work by *Zhang et al.* [2008], the land surface partitioning of the regional model into sensible and latent flux has been substantially improved in the Amazonian rainforest areas. Ensemble model simulations are used to ensure that the changes induced by aerosol radiative forcing are significantly greater than the random errors due to the internal variability of the model.

[4] Biomass burning peaks from August to October with maximum concentrations in Southeastern Amazonia. This peak coincides with the monsoon transition from dry to wet season, characterized by rapid expansion of rainy area from northwestern to southern Amazonia [Kousky 1988; *Marengo et al.*, 2001]. This monsoon circulation transition is initiated by an increase of surface radiation and resultant increases in latent and sensible fluxes, which lead to a destabilization of the atmospheric thermodynamic structure and an increase of moisture transport to Amazonia [*Li and Fu*, 2004]. In addition, cold front incursions from extratropical South America lift warm and humid surface air in Southern Amazonia and trigger large-scale increase of rainfall and wet season onset [*Li and Fu*, 2006]. This work explores whether or not the radiative effect of smoke

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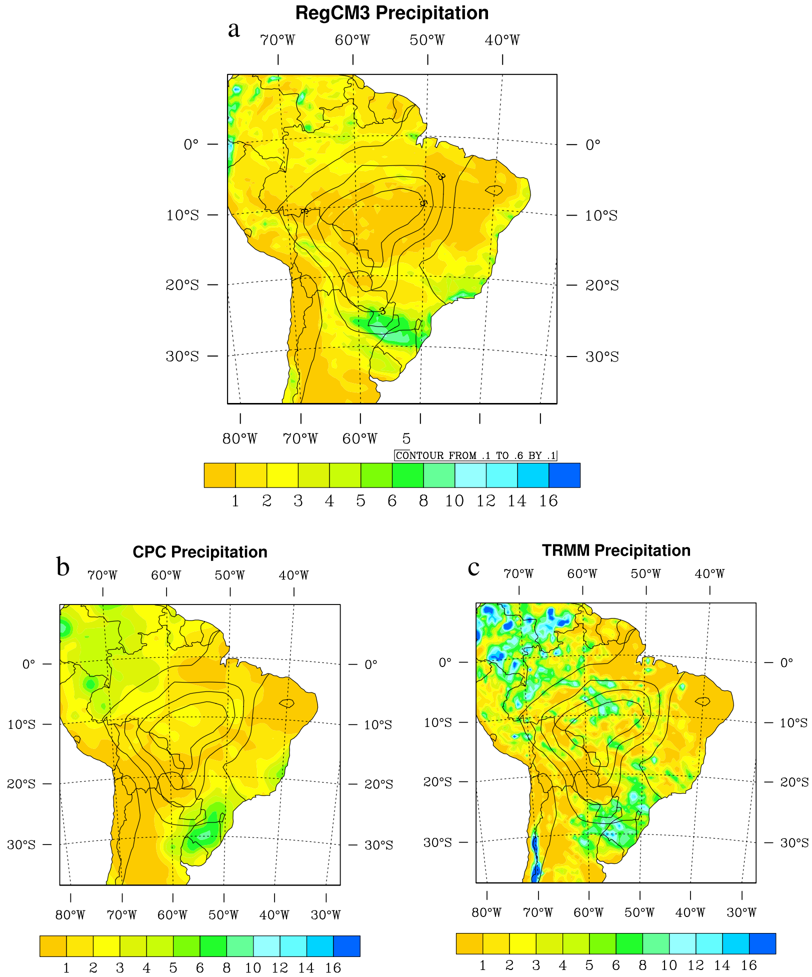

Figure 1. Monthly mean precipitation (shades, unit: mm/day) derived from (a) RegCM3 CONT simulation, (b) CPC, and (c) TRMM for September 2002. The prescribed aerosol optical depth (AOD) is shown by contours with interval of 0.1.

aerosols can influence these processes during the monsoon circulation transition. In doing so, it aims to clarify the mechanisms through which smoke aerosols influence large-scale rainfall patterns.

2. Model Description and Evaluation

[5] The numerical model applied to this study is the Abdus Salam Institute for Theoretical Physics Regional Climate Model, Version 3 (RegCM3) [*Pal et al.*, 2007]. It reasonably simulates the spatial distribution of rainfall over South American (Figure 1) and the timing of rainy season [*Rauscher et al.*, 2007]. Its domain ranges from 20°W to 80°W, 5°N to 35°S, covering most of the South America. Its atmosphere has 18 levels, with 7 levels in the lowest 1.5 km of atmosphere, and its horizontal resolution is 60 km. Initial and boundary conditions are prescribed for 2002 using the National Center for Environmental Prediction (NCEP) Reanalysis datasets. A more detailed description of RegCM3 and modifications to improve the partitioning of surface energy are given by *Zhang et al.* [2008].

[6] The RegCM3 is integrated from August to October, the peak biomass burning season. Two 10-member ensemble experiments are conducted to reduce the magnitude of the random errors of surface radiative fluxes to less than that of the aerosol radiative forcing at the surface. The control experiment does not include smoke aerosol (referred to as CONT). The aerosol experiment includes the direct radiative forcing of the aerosols as determined by the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model [*Yu et al.*, 2003; *Chin et al.*, 2002] (referred to as AERO). The aerosol influence on cloud microphysics is not included in this study. Aerosol is uniformly distributed from the surface to 2 km. Each of the ensemble simulations starts from a different initial condition corresponding to that for one of the days during August 1st to August 10th 2002. The direct and semi-direct effects of the aerosols can change the lapse rate, ABL turbulence, water vapor and thus cloud cover. *Zhang et al.* [2008] provide more details about the experimental design, spatial distribution of aerosol radiative properties, and sensitivity tests of the aerosol radiative forcing to changes of the vertical location of the aerosol layer, as well as to diurnal and sub-monthly variations of the aerosol optical depth.

[7] Figure 1 compares the spatial distribution of rainfall for September obtained from the ensemble RegCM3 CONT simulations (Figure 1a), with those of the NOAA Climate Prediction Center data (CPC) (resolution 1° × 1°, Figure 1b),

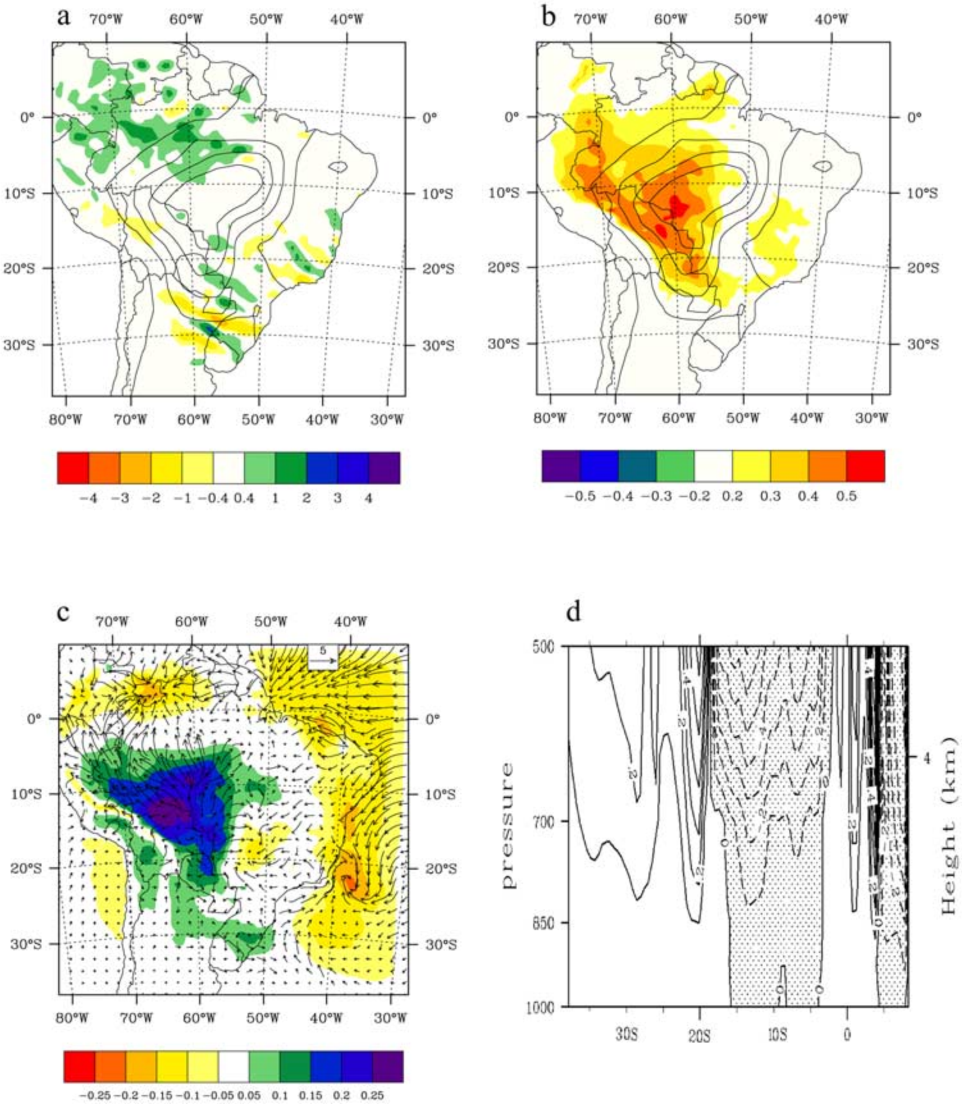

Figure 2. (a) Difference of monthly mean precipitation (shades, unit: mm/day) between the ensemble mean of AERO and that of the CONT simulations for September. AOD is shown by contours with interval of 0.1. (b) Difference of the potential temperature lapse rate (unit: K/km) in the lower troposphere from 960 hPa to 600 hPa between the AERO and CONT simulations for September. (c) Difference of the surface pressure (shades, units: hPa) and moisture flux at 925 hPa (vectors, units: g kg^{-1} ms^{-1}) between the AERO and CONT simulations for September. (d) Difference of the vertical velocity (m s^{-1}) along the longitude-height cross-section at 65°W. Dashed lines and shaded areas represent downward motion. Solid lines present upward motion.

and the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission data (TRMM) (resolution 0.5° × 0.5°, Figure 1c) for September. The modeled rainfall centers are located in northwestern Amazonia and in the area of southeastern Brazil, Paraguay and northeastern Argentina. Their locations agree qualitatively with those indicated by both in situ (CPC) and satellite (TRMM) rainfall observations. Quantitatively, the rain rate in northwestern Amazonia is underestimated but the rain rate in southeastern Brazil, Paraguay and northeastern Argentina agrees well with the observations.

3. Results

[8] Our analysis mainly focuses on September at the peak of the smoke aerosol optical depth. Figure 2a shows the difference in rainfall between AERO and CONT in September, i.e., the influence of aerosols on rainfall. Rainfall change in the smoke area is small (about 0.02 mm day^{-1} or 2%) despite heavy aerosol loading. However, the increase of rainfall is much more substantial (0.36 mm day^{-1} or 16%) over equatorial Amazonia where the smoke aerosol load is weak. The rainfall anomaly patterns induced by aerosols over northwestern Amazonia are consistent with the patterns of cloud liquid water and circulation anomalies at 850 hPa [*Zhang et al.*, 2008, Figure 13]. Figure 2a also shows a dipole pattern of rainfall change between southeastern Brazil and northeastern Argentina (20°–35°S, 40°–65°W). What processes could cause the aforementioned patterns of rainfall change? Figure 2b shows change of potential temperature lapse rate in the layer from the 960 hPa to the 600 hPa altitude

between the AERO and CONT simulations. The increase of the lapse rate, thus the thermodynamic stability, in the smoke center is about equally contributed by the potential temperature warming at 600 hPa and cooling at 960 hPa in the AERO simulations vs. the CONT simulations. Because the warming at 600 hPa (around 1°C) is well above the aerosol layer, it is likely due to enhanced middle troposphere subsidence, especially on eastern Andes. Figure 2c shows an increase of surface pressure occurs in the smoke center relative to the CONT simulations, as expected from a more stable lapse rate in the lower troposphere and increased subsidence. Such an increase of surface pressure can weaken the southward pressure gradient force, which is needed to drive wind and moisture transport toward southern Amazonia as a key step for dry to wet monsoon circulation transition in that region. Consequently, moisture transport to southern Amazonia is reduced and the retention of moisture in northern Amazonia enhanced, leading to a dipole of moisture divergence change between the northwestern and southern Amazonia shown in Figure 2c. These changes do not lead to significant rainfall decrease in southern Amazonia, because the meteorological conditions are mostly already stable for rain in September even without aerosols [*Fu et al.*, 1999, Figure 1]. However, the anomalous moisture convergence does significantly increase rainfall and promote ascending motion in the northwestern Amazonia where the atmosphere is thermodynamically unstable (Figure 2d). It is similar to that found in past nuclear winter studies in which smoke aerosol causes ascending motion at the edge of the plume [*Giorgi and Visconti*, 1989].

[9] What could cause the other dipole pattern of rainfall change in the southeastern subtropical South America (20°–35°S, 40°–65°W)? Previous studies suggest that the incursion of extra tropical cold fronts and South American Low-level Jets (SALLJ) have important contributions to rainfall in this region, especially during austral winter and spring [*Garreaud and Wallace*, 1998; *Silva and Berbery*, 2006]. Previous studies characterized cold fronts and associated baroclinic wave activities by a storm track index [e.g., *Xie and Arkin*, 1997; *Nakamura et al.*, 2002]. We use the daily change of eddy meridional temperature flux at 700 hPa ($\delta\overline{v'T'}_{700\ hPa}$) [*Hoskins and Valdes*, 1990]. Figure 3a shows the differences in $\delta\overline{v'T'}_{700\ hPa}$ and rainfall between the AERO and CONT ensemble simulations, i.e., the change of these fields induced by the smoke aerosol radiative forcing. A negative value of $\delta\overline{v'T'}_{700\ hPa}$ represents stronger eddy transport of heat or anomalous cyclonic activity in Southern Hemisphere. The pattern of $\delta\overline{v'T'}_{700\ hPa}$ simulated by the RegCM3 CONT (not shown) is similar to the observed climatology of $\delta\overline{v'T'}_{700\ hPa}$ of *Kodama and Tamaoki* [2002, Figure 10b]. This agreement with observations suggests that the RegCM3 probably adequately captures the baroclinic wave activities in the region. The sea-saw shape of the change of $\delta\overline{v'T'}_{700\ hPa}$ is similar to that of the pattern of rainfall change but with a 90° phase shift, namely the rainfall anomalies are the maximum where the $\delta\overline{v'T'}_{700\ hPa}$ anomalies are near zero. Such a phase shift is expected because anomalous mid-tropospheric vertical motion, which causes rainfall anomalies, is driven by upper troposphere divergence or convergence induced by change in gradient wind. The gradient wind change is maximum in transition areas between anomalous cyclonic flow (trough) and anticyclonic flow (ridge) associated with the mid-latitude synoptic waves. The pattern of precipitation change shown in Figure 3a is robust, qualitatively the same in as much as 80% of the individual runs that are used to compute the ensemble mean. Such a stationary response in rainfall anomalies is presumably shaped by the topography and low-level jets of South America. The similarity of the patterns of the change of rainfall and $\delta\overline{v'T'}_{700\ hPa}$ (Figure 3a) suggest that increasing stability in southern Amazonia may have pushed extra tropical wave activity poleward, and so caused the rainfall changes in the subtropical eastern South America. Figure 3b shows the change of meridional winds in the troposphere along 20°S across South America. The northerly wind anomalies below 750 hPa between 40°W and 60°W are contributed by an enhanced low-level wind speed associated with SALLJ, instead of the frequency of occurrence of the SALLJs (not shown). Stronger SALLJs in turn increase moisture export from the southeastern Amazonia to southern Brazil, Paraguay and northern Argentina [*Berbery and Barros*, 2002]. Thus, an enhanced northerly lower tropospheric wind and its moisture export from Amazonia also contribute to the rainfall increase in these subtropical and extratropical regions.

4. Conclusions and Discussion

[10] Simulations are carried out with the Abdus Salam Institute for Theoretical Physics Regional Climate Model (RegCM3) to test the impacts of smoke aerosol radiative effect during the dry to wet transition season in Amazonia. The modeled radiative forcing by smoke aerosols reduces surface solar flux and stabilizes the lapse rate from the surface to the top of the smoke layer in southern Amazonia where smoke center is located. In addition, the aerosol radiative forcing also warms the atmosphere well above the smoke layer presumably through an enhanced mid-troposphere subsidence. These changes increase the stability of the entire lower troposphere and surface pressure in southern Amazonia. The latter weakens the southward surface pressure gradient, leading to anomalous moisture divergence in the south and moisture convergence in northwest of Amazonia. Furthermore, the stabilized atmosphere and increased surface pressure in southern Amazonia due to smoke aerosols also appear to inhibit cold air incursion and increase moisture export to subtropical South America. The latter two changes increase rainfall over northwestern Amazonia and the area of southeastern Brazil, Paraguay and northeastern Argentina outside of smoke center. Within the smoke center, rainfall change is small presumably because the atmosphere is already stable to convection without aerosols. Our results suggest that the dynamic response to radiative forcing by smoke aerosols during the transition period of the South America monsoon can have a stronger influence on rainfall change than the local thermodynamic impact of aerosols. Whether and how this result may change for substantially different aerosol radiative forcing needs to be further tested (Vendrasco et al., submitted manuscript, 2008).

[11] Previous studies have established that the monsoon circulation transition from dry to wet season is driven mainly by three mechanisms [*Li and Fu*, 2004, 2006]: 1) it is initiated by an increase of surface solar flux which

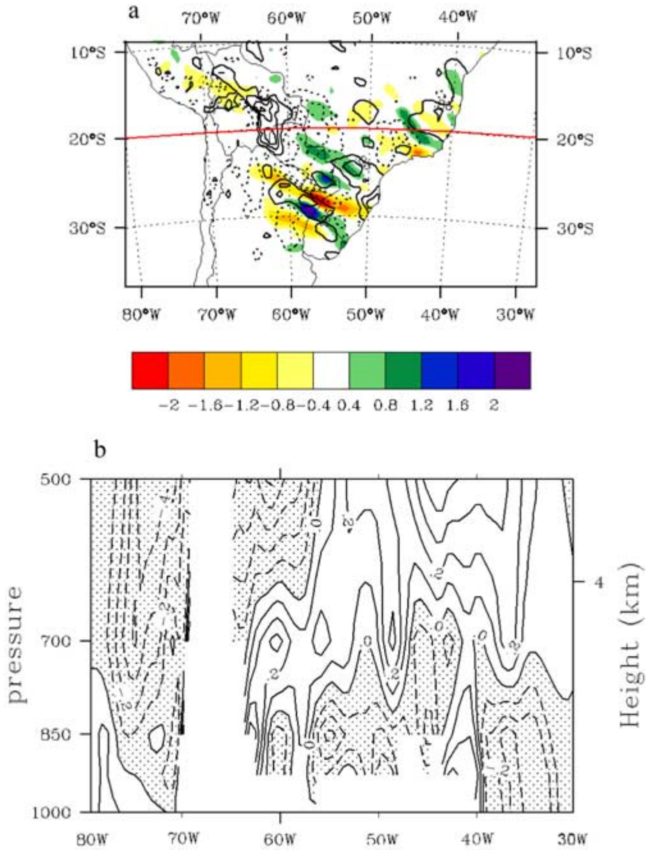

Figure 3. (a) Changes of $\delta\overline{v'T'}_{700\ hPa}$ (contours) superimposed on the change of precipitation (shades) between ensemble mean of AERO and that of CONT in September. Solid and dotted contour represent positive or negative change of $\delta\overline{v'T'}_{700\ hPa}$. The line along 20°S indicates the geographic location of the latitude-height cross-section shown in Figure 3b. (b) Change of the meridional wind along the latitude-height cross-section at 20°S indicated in Figure 3a. Solid contours represent positive or southerly meridional wind change and dashed contours and shaded areas represent negative or northerly meridional wind change. Blank area indicates the topography.

increase the surface air buoyancy and instability for moist convection; 2) an increase of convection reduces surface pressure in southern Amazonia and increases moisture transport; 3) cold front incursions lift buoyant surface air over Amazonia and trigger onset of the wet season. The smoke aerosol radiative forcing as shown by our ensemble regional climate model simulations could interfere with all three mechanisms that drive the monsoon circulation transition and rainfall migration to southern Amazonia. In particular, it reduces surface solar flux and stabilizes the atmosphere lapse rate in the lower troposphere in the biomass burning areas in Southern Amazonia, hence weakens the increase of surface sensible and latent flux that initiate the monsoon transition. It increases surface pressure in Southern Amazonia to decrease southward surface pressure gradient needed for enhanced moisture transport, as a part of normal monsoon circulation transition. Finally, by reducing cold air incursions into the southern Amazon it weakens the triggering mechanism for wet season onset. Thus, the circulation changes induced by the smoke aerosols could slow down or weaken the normal monsoon circulation transition. Validation of these mechanisms suggested by the ensemble RegCM3 experience using existing observations is not feasible, due to strong coupling between dry anomalies and biomass burning in terms of their influence on large-scale circulation and rainfall. Future observations that allow us to isolate the climatic influence of biomass burning aerosols from that of the dry climatic anomalies forced by other factors such as SST change in adjacent oceans are needed to validate the mechanisms of the smoke aerosols influences shown in this study.

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